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FULL LENGTH ARTICLE

Mechanical properties of self-compacted fiber concrete mixes

Mounir M. Kamal [a], **Mohamed A. Safan** [a], **Zeinab A. Etman** [a,*], **Bsma M. Kasem** [b]

[a] *Department of Civil Engineering, Faculty of Engineering, Menoufia University, Egypt*
[b] *Civil Engineer and Postgraduate Fellow, Ministry of irrigation and Water Resources, Egypt*

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KEYWORDS

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Polypropylene fibers;
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Compressive strength

Abstract Increased productivity and improved working environment have had high priority in the development of concrete construction over the last decade. The major impact of the introduction of self-compacting concrete (SCC) is connected to the production process. The productivity is drastically improved through the elimination of vibration compaction and process reorganization. The working environment is significantly enhanced through avoidance of vibration induced damages, reduced noise and improved safety. Additionally, SCC technology has improved the performance in terms of hardened concrete properties like surface quality, strength and durability. The main objective of this research was to determine the optimum content of fibers (steel and polypropylene fibers) used in SCC. The effect of different fibers on the fresh and hardened properties was studied. An experimental investigation on the mechanical properties, including compressive strength, flexural strength and impact strength of fiber reinforced self-compacting concrete was performed. The results of the investigation showed that: the optimum dosage of steel and polypropylene fiber was 0.75% and 1.0% of the cement content, respectively. The impact performance was also improved due to the use of fibers. The control mix specimen failed suddenly in flexure and impact, the counterpart specimens contain fibers failed in a ductile manner, and failure was accompanied by several cracks.

Introduction

The concept of self-compacting concrete (SCC) was proposed in 1986 by Hajime Okamura [1], but the prototype was first developed in Japan in 1988 by Ozawa [2]. This new concrete was deliberately designed to be able to fill every corner of the form and encapsulate all reinforcements only under the influence of gravitational forces, without segregation or bleeding. These advantages make SCC, particularly useful wherever placing is difficult as in heavily reinforced concrete members or

* Corresponding author. Tel.: +20 1009727355; fax: +20 482238232.
E-mail address: dr_zeinab_2006@yahoo.com (Z.A. Etman).
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in complicated work forms. Through extensive research, it has been established that the addition of fibers to concrete considerably improves its structural properties such as compressive strength, static flexural strength, impact strength, tensile strength, ductility and toughness [3–10]. Felekoğlu et al. [11] reported that using SCC with its improving production techniques is increasing every day in concrete production. Domone [12] carried out an analysis for 68 case studies addressing the applications of SCC. He calculated the mix proportions of SCC. 31.2% by volume of the mix were a coarse aggregate. The paste content was 34.8% by volume. The powder content was 500 kg/m^3; water/powder ratio was 0.34 by weight, and the fine aggregate/mortar was 47.5% by volume. Uysal and Yilma [13] studied the effect of using different types of mineral admixtures on the fresh and hardened properties of self-compacting concrete. They mentioned that the use of marble powder was the most suitable with regard to the properties of fresh SCC. On the other hand, Khaleel et al. [14] reported that the coarse aggregate properties had a direct effect on achieving SCC. Maximum size, texture and type of coarse aggregate were the factor effects on the flowabilty of concrete. They found that the flow-ability of SCC decreases with the increase in the maximum size of coarse aggregate and using crushed aggregate with the same water to powder ratio and superplasticizer dosage. However, mix design methods and testing procedures are still developing. Zhu and Bartos [15] studied that permeation properties, which include permeability, absorption, diffusivity, etc., have been widely used to quantify durability characteristics of SCC. The results indicated that SCC mixes had significantly lower permeability than the vibrated normal reference concretes of the same strength grades. Furthermore, SCC mixes containing no additional powder but using a viscosity agent were found to have considerably higher diffusivity than reference mixes, and other SCC mixes. However, it is necessary assuring that this enhancement on the mechanical properties is not accompanied by a detrimental effect on the durability properties. Conventional fiber reinforced concrete is a special type of concrete that has been strengthened by adding fibers to the wet concrete mix. Concrete is quite brittle and while high levels of compressive strength can be achieved; the tensile strength is relatively low, which makes it likely to crack under many conditions. Fiber reinforced concrete is less probable to crack than conventional concrete. In the early years of the 20th century, asbestos fibers were added to concrete. In 1960s, a variety of fibers, including polypropylene, glass, and steel fibers were used in concrete [16]. Fiber reinforced concrete is commonly used in pavements and floors. It can also be used in foundations, pillars, precast forms, and beams in combination with traditional steel reinforcements. Fibers are usually used in concrete to resist cracking due to plastic and drying shrinkage. Numerous researchers have studied the effects of fibers on plastic shrinkage cracking behavior as reported in ACI 544.5R-10. A general observation is that thin fibers are more impressive in reducing the width of plastic shrinkage cracks than thick fibers as reported in ACI 544.5R-10 [17]. Most thin-diameter micro fibers with a high specific fiber surface area are particularly effective in reducing plastic shrinkage cracking [18]. Moreover, the use of fibers helps in reducing the permeability of concrete and its tendency to bleed [14]. A number of studies have been conducted to investigate the relationship between fiber reinforced concrete (FRC) and water permeability [18,19]. Some types of fibers produce greater impact, abrasion and shatter resistance of concrete. The amount of fibers added to a concrete mix is measured as a percentage of the total volume of the composite (concrete and fibers) and termed the volume fraction (Vf) [19]. The effect of fibers on the mechanical properties of concrete such as compressive strength, splitting tensile strength and flexural strength was reported by Alonso, 2008, Sena-Cruz, 2004 [20] and many other researchers. Some studies on the impact resistance of fiber reinforced concrete showed that self-compacted reinforced composites under impact were capable of dissipating much higher energy compared with conventional fiber reinforced concrete with polymeric or steel fiber [21]. Bindiganavile and Banthia, 2002 observed that the measured impact response was highly dependent on the characteristics of the dropping weight of the impact machine used for testing. Results appear to be far less sensitive to the mass of the hammer than to the drop height [21–23]. When self-compacting concrete becomes so widely used that it is seen as the "standard concrete" rather than a "special concrete" it will be possible to have durable and reliable concrete structures that require very little maintenance work. The development of SCC was an important step toward efficiency at building sites, rationally producing prefabricated concrete elements, better working conditions and improved quality and appearance of concrete structures. By adding fibers to SCC it is possible to enhance the performance of concrete structures. Fiber self-compacting concrete combines the benefits of SCC in the fresh state and an enhanced performance of fiber reinforced concrete in the hardened state.

Experimental program

To achieve the aim of the research, a two-stage program was conducted. In the first stage, different mixes were prepared to specify the best mix which achieves the requirements of Technical Specification for SCC. In the second stage, six mixes were prepared to determine the optimum content of fibers used in the fresh state of SCC, which are based on the finding of the first stage. A total of 90 cubes $10 \times 10 \times 10$-cm were tested to determine the compressive strength of the mixes at 7 and 28 days. Cylinders of 10 cm in diameter and 20 cm in length were studied to determine the splitting tensile strength of the mixes. To determine the flexural strength of mixes and impact strength; $10 \times 10 \times 50$-cm prisms were used.

Materials

Well graded siliceous sand was used with a specific gravity of 2.60, absorption of 0.78%, and a fineness modulus of 2.61. A coarse aggregate of crushed dolomite with maximum nominal sizes of 10 mm and 14 mm was used, with a specific gravity of 2.64 and absorption of 0.76%. Locally produced Portland cement (CEMI: 42.5 N) conforming to the requirements of Egyptian Standard Specifications (2005/373) was used. Imported class (F) fly ash meeting the requirements of ASTM C618 [24] with a specific gravity of 2.1 was used. Fly ash was added by 10% of the cement content. The cement content was 400 kg/m^3 and the water powder ratio (W/P) ranged from (0.35 to 0.4). Tap water was used for mixing the concrete. A high range water reducer (HRWR) with a trade name; Addicrete BVF was used as superplasticizer meeting the requirements of ASTM C494 (types A and F) [25]. The admixture

Table 1 Concrete trail mix proportions of self-compacted concrete mixes (kg/m^3).

	Mix No.	Cement	Sand	Dolomite	Fly ash	W/P	% HRWR
M.N.S. 10 mm	1	400	972	864	40	0.35	2
	2		972	862			2.5
	3		972	860			3
	4		968	859			3.25
	5		967	858			3.5
M.N.S. 14 mm	6		925	755			2.5
	7		923	754			3
	8		921	753			3.5
	9		920	752		0.4	2.5

Table 2 Rheological properties of trail self-compacted concrete mixes.

Mix no		Test method								Notes
		Slump flow test			J-ring test			V-funnel test		
		D (mm)	T (s)	$T_{50\ cm}$ (s)	D (mm)	H_1–H_2 (MM)	$T_{50\ cm}$ (s)	T (s)	Velocity	
M.N.S. 10 mm	1	450	25.69	1.5	450	25	–	37.58	1.73	Viscosity too high
	2	470	37.58	2.0	450	26	–	26.87	2.42	Viscosity too high
	3	550	26.87	8	500	23	5.2	25.69	2.53	Viscosity too high
	4	565	16.78	6.5	540	17	3.36	22.35	2.91	Viscosity too high + Segregation
	5	780 (700 mm)*	12.25	13 (2–5 s)*	780	2 (0–10 mm)*	3	14 (6–12 s)*	4.64	Bleeding + segregation
M.N.S. 14 mm	6	670	6.8	2.86	650	7	9.27	12.25	5.31	Bleeding
	7	720	5.98	2	700	5	7.68	6.8	9.56	Segregation
	8	765	14	18.6	780	10	1.27	5.98	10.89	Viscosity too high
	9	750	6.25	4.57	670	3.5	4.76	6.25	10.4	Very good SCC

D: final diameter of the concrete = $[D_1 + D_2]/2$, T_{50cm}: time for the concrete diameter to reach 50 cm (s), H_1–H_2: the difference of the height of the concrete just before and after the ring, T: flow-through time (s).
* Requirements of technical specification of self-compacted concrete [27].

Fig. 1 J-ring test for passing ability of mix 9.

Fig. 2 Slump flow test for flowability of mix 9.

is a brown liquid having a density of 1.18 kg/L at room temperature. The amount of HRWR ranged from (2.0 to 3.5%) of the cement weight was used. The fibers used to improve the mechanical properties in mixes had a trade name fiber mesh 300-e3 produced by SI Concrete systems, USA. 20 mm length polypropylene fibers were used. According to the manufacture data sheet, the fibers have a specific gravity of 0.91 and comply with ASTM C1116 [26] Type III. Steel fibers also were used. The absolute volume method was used to design the required trial mixes.

Casting and testing procedures

Coarse aggregate, fine aggregate, and the cement were mixed for at least 1 min in the dry state before the water, and admixtures have been added. The mixing time after slurry (water, fly ash, and HRWR) was added for (3–4) minutes to ensure full mixing of the SCC. In case of fiber self-compacted concrete, the fibers were added to the dry components before the slurry.

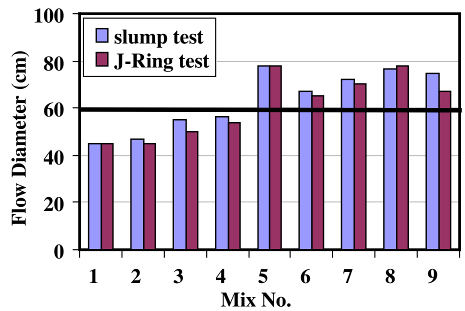

Fig. 3 Relationship between flow diameter of SCC and other mixes using different rheological tests.

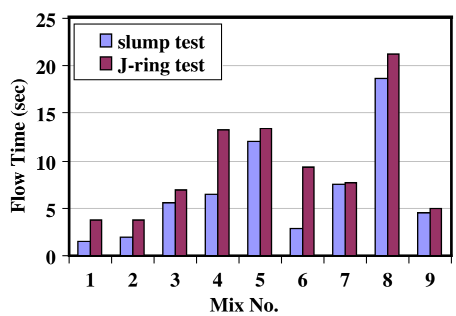

Fig. 4 Relationship between flow time of SCC mix and other mixes using different rheological tests.

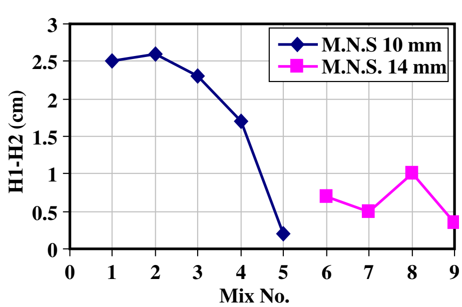

Fig. 5 Relationship between (H1–H2) of SCC mix and other mixes using J-ring test.

The properties of fresh SCC were determined by different methods, which included the normal slump test, V-funnel test and J-ring test as illustrated in Table 2. The concrete specimens were cast and kept at the steel molds for 24 h. After 24 h, the specimens were removed from the molds and submerged in clean water at 20 °C until taken out for testing. Compressive strength testing machine with 2000 KN capacity was used in the determination of the compressive strength and splitting tensile strength. Flexural strength testing machine with 100 KN capacities was used in the determination of the flexural strength of the prism. The flexural strength was determined by the four points loading that having the same dimensions' concrete impact test beam specimens.

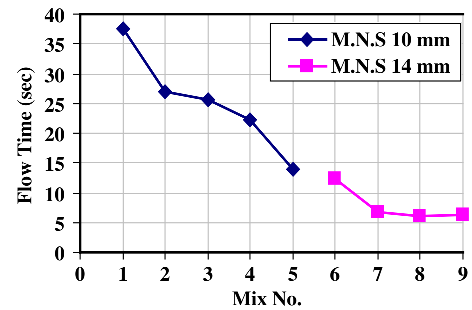

Fig. 6 Relationship between Flow Time of SCC Mix and other Mixes Using V-Funnel Test.

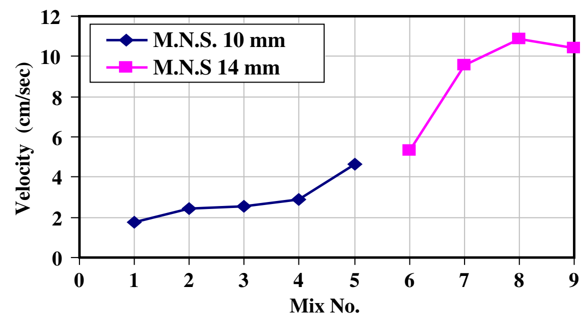

Fig. 7 Relationship between velocity of SCC mix and other mixes using V-funnel tests.

Test results

First stage

In this stage, nine mixes were prepared to specify the best mix which achieves the requirements of Technical Specification for SCC [27]. Coarse aggregate (dolomite) with a maximum nominal size of 10 mm and 14 mm was used to achieve the requirements as illustrated in Table 1. The properties of fresh SCC were determined by different methods as illustrated in Table 2.

Workability for self-compacted concrete mixes

Table 2 illustrates a summary of the fresh self-compacting concrete properties. Figs. 1 and 2 show the properties for the fresh self-compacted concrete mixes. It is clear from Figs. 3–7, the basic requirements of flowability as specified by technical specification for self-compacted concrete are satisfied for mix 9. For slump test, the flow diameter and the flow time at 50 cm were (75 cm) and (4.57 s), respectively. For V-funnel test the flow time was (6.25 s). These results indicate that the requirements for self-compacted concrete were achieved. The workability values are maintained by adding suitable quantities of materials and super-plasticizers.

Second stage

Based on results of first stage, mix (9) achieved the requirement of SCC. So, the second stage of the experimental program was conducted to add the fibers to SCC mix. Six mixes were prepared at this stage, after achieving the requirement of technical specification for SCC mixes in the first part as illustrated in mix (9). Different percentages of fiber (steel and polypropylene

Table 3 Concrete mix proportions (kg/m^3).

	Mix No.	Cement	Sand	Dolomite	Fly ash	W/P	% BVF	% Fiber	
								Steel fibers	Polypropylene fibers
M.N.S. 14 mm	9	400	920	752	40	0.4	2.5	–	–
	SSCC1 (10)		920	752			2.5	0.5	–
	SSCC2 (11)		920	752			2.5	0.75	–
	SSCC3 (12)		920	752			2.5	1.0	–
	PSCC1 (13)		920	752			2.5	–	0.5
	PSCC2 (14)		920	752			2.5	–	1.0
	PSCC3 (15)		920	752			2.5	–	1.5

fiber) were added to the fresh self-compacted concrete. The percentages of steel fiber used were (0.5%, 0.75% and 1.0%) of the cement content. The percentages of polypropylene fiber used were (0.5%, 1.0%, and 1.5%) of the cement content. The optimum content of fiber was investigated. Tables 3 and 4 illustrated the concrete mix proportions and the rheological properties of fiber self- compacted concrete mixes.

Workability for fiber self-compacted concrete mixes

Table 4 illustrates a summary of the fresh fiber self-compacting concrete properties. It is clear from Figs. 8–14, the basic requirements of flowability as specified by technical specification for self-compacted concrete are satisfied for SSCC2 and PSCC2 compared with the control mix (mixes 9). The flow diameter was (70 and 72 cm) SSCC2 and PSCC2, respectively. The flow time at 50 cm was (4.89 and 5.0 s) for SSCC2 and PSCC2, respectively. For V-funnel test the flow time was (11.2 and 7.05 s) for SSCC2 and PSCC2, respectively. These results indicate that the requirements for SCC were achieved.

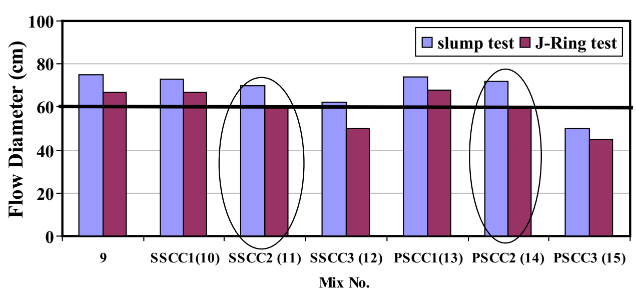

Fig. 8 Relationship between Flow Diameter and other Mixes of Fiber Self-Compacted Concrete.

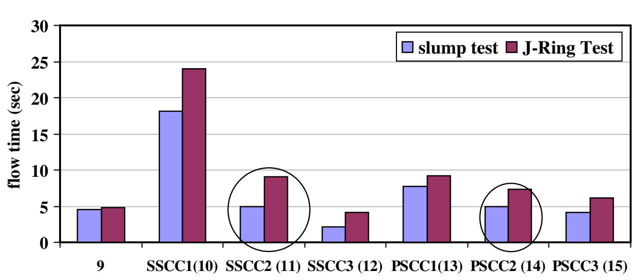

Fig. 9 Relationship between flow time and other mixes of fiber self-compacted concrete.

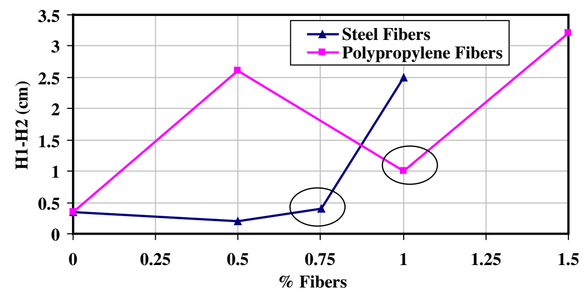

Fig. 10 Relationship between (H1-H2) of Fiber Self-Compacted Concrete Mix and Percentage of Used Fiber.

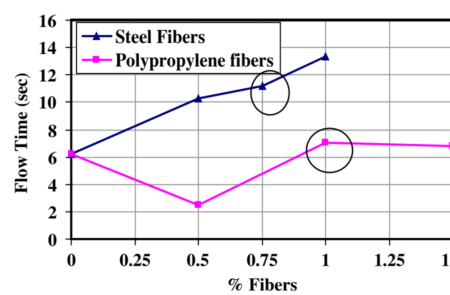

Fig. 11 Relationship between flow time of fiber self-compacted concrete mix and percentage of used fibers.

It is noticed that the technical specification for SCC do not cover the properties of fiber self-compacted concrete.

Test set-up for impact Load

Test set-up was prepared to get the impact strength of self-compacted concrete and fiber self-compacting concrete at 28 days. A 2 kg iron ball was used to make an impact load on the tested specimens from a 1.2 m distance. The striking head of the drop iron ball had a hemispherical tip with a radius of 5 cm; Fig. 13 shows the test set-up. The specimen has been placed in impact testing installation, and it has been fixed using G-clamps. The specimen was supported over a span of 45 cm with specially designed devices, allowing it to freely rotate while preventing it from moving out of displacement. The span of the concrete beams tested was accurately adjusted for specimen of size $10 \times 10 \times 50$ cm. The falling ball was adjusted to dropping on the middle point of the tested specimens. The

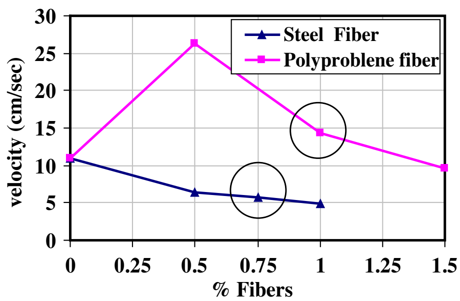

Fig. 12 Relationship between velocity of fiber self-compacted concrete mix and percentage of used fibers.

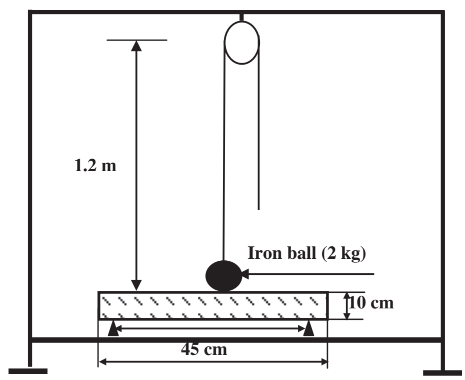

Fig. 13 Test set-up for impact testing installation.

blows were repeated until the 1st crack appeared. The crack propagation after each blow was marked on the specimen. The experiment was continued until the spalling occurs on the compression face of the specimen. The number of blows required for spalling for the full width on the compression face was noted, and the crack pattern was marked on the specimen. A comparison between the properties of fresh self-compacted concrete and fiber self-compacted concrete was illustrated in Figs. 14–18.

Effect of fiber on bleeding

Based on the experimental study, it can be concluded that the addition of fibers in concrete mixes gives a reduction in bleeding. The homogeneity of the mixes improved by the reduction in bleeding was noticed. The properties of fresh fiber SCC are illustrated in Table 4. Clearly, the SCC mix containing 0.75% steel fiber by cement weight was the best mix (SSCC2) as

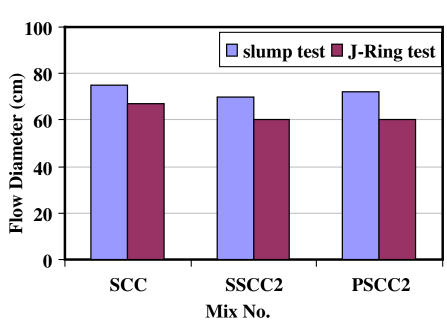

Fig. 14 Relationship between flow diameter and other mixes.

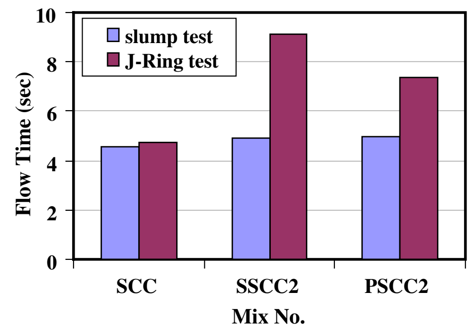

Fig. 15 Relationship between flow time and other mixes.

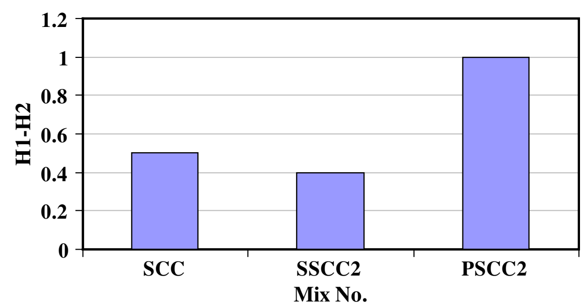

Fig. 16 Relationship between (H_1–H_2) and other mixes using J-ring test.

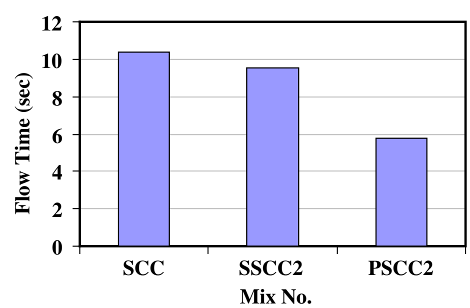

Fig. 17 Relationship between flow time and other mixes using V-funnel test.

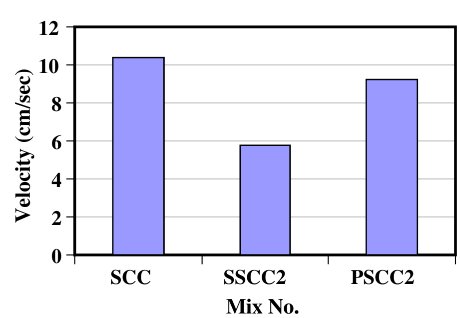

Fig. 18 Relationship between Velocity and other Mixes Using V-funnel Test.

illustrated in Figs. 8–12. The optimum value for polypropylene in the self-compacted concrete was 1% by cement weight for the mix (PSCC2) as illustrated in Figs. 8–12.

Mechanical properties of fiber self-compacted concrete mixes

Self-compacted concrete mixes containing steel or polypropylene fibers were prepared using 14-mm crushed dolomite as coarse aggregates. Different percentages of fibers were used. Fig. 19 shows the compressive strength for the fibers SCC mixes under investigated. The compressive strength ranged between 30.3 and 42.3 Mpa at 28 days. An increase was observed, which ranged between 33% and 40% for steel fiber SCC mixes compared with plain self-compacting concrete. Increase in compressive strength for polypropylene fiber SCC mix, ranged between 12% and 15% compared with the SCC mix observed. Increase in the compressive strength for the mixes with polypropylene fibers is compared to that with steel fiber. It is worth mentioning that compressive strength of polypropylene fiber SCC mixes was greater by about 17% in comparison with the steel fiber SCC mixes. Fig. 20 shows the fracture modulus (the fracture modulus f_r values reported in Table 5.) divided by the square root of the compressive strength f_{cy} and a plot of the ACI-318 code equation for predicting the fracture modulus (SI units):

$$f_r = 0.622\sqrt{f_{cy}} \tag{1}$$

Fig. 19 shows that the fracture modulus was safely predicted using Eq. (1). It can also be seen that the fracture modulus tended to increase in both polypropylene and steel fiber self-compacted mixes having lower compressive strength.

Impact resistance

The response of a structural element to impact depends on the interaction between the impacting body and the structure. Nemours factors described impact strength, which relative

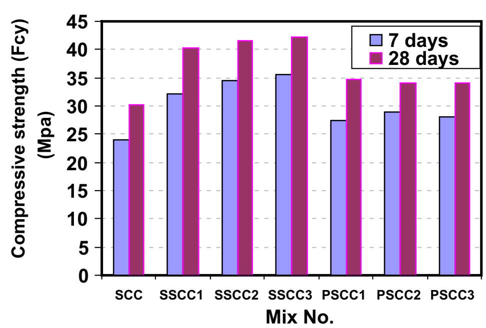

Fig. 19 Compressive strength for different mixes.

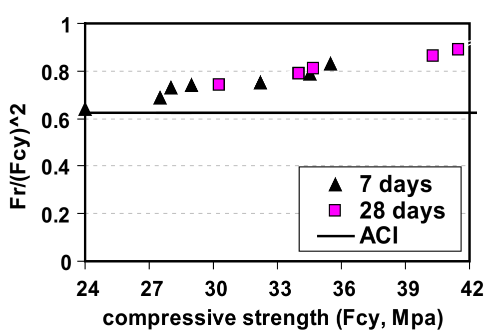

Fig. 20 Relation between fracture modules and compressive strength.

Table 4 Rheological properties of fiber self-compacted concrete mixes.

Mix no	Test method	Slump flow test			J-ring test			V-funnel test		Notes
		D (mm)	T (s)	$T_{50\ cm}$ (s)	D (mm)	H_1–H_2 (MM)	T_{50} (s)	T (s)	Velocity	
M.N.S. 14 mm	9	750	6.25	4.57	670	3.5	4.76	6.25	10.4	SCC
	SSCC1 (10)	730	20.14	18.17	670	2	24.14	10.26	6.33	Viscosity too high
	SSCC2 (11)	700	8.55	4.89	600	4	9.1	11.2	5.8	SCC
	SSCC3 (12)	625	7.10	2.2	500	25	4.1	13.37	4.86	Viscosity too low
	PSCC1 (13)	740	14.8	7.69	680	26	9.17	2.47	26.32	Viscosity too high
	PSCC2 (14)	720	7.27	5.0	600	10	7.37	7.05	9.22	SCC
	PSCC3 (15)	500	8.7	4.2	450	32	6.2	6.8	9.55	Viscosity too high
		(700 mm)*		(2–5 s)*		(0–10 mm)*		(6–12 s)*		

D: final diameter of the concrete = $[D_1 + D_2]/2$, T_{50cm}: time for the concrete diameter to reach 50 cm (s), H_1–H_2: the difference of the height of the concrete just before and after the ring, T: flow-through time (s).

* Requirements of technical specification of self-compacted concrete [27].

Table 5 Compressive strength and flexural strength of self-compacting concrete and fiber self-compacting concrete.

Mix no	Compressive strength (MPa)		Flexural strength (f_r) (MPa)	
	7 days	28 days	7 days	28 days
SCC (9)	24.0	30.3	3.13	4.07
SSCC1(10)	32.2	40.3	4.26	5.46
SSCC2 (11)	34.5	41.5	4.64	5.73
SSCC3 (12)	35.5	42.3	4.95	6.05
PSCC1(13)	27.5	34.7	3.62	4.77
PSCC2(14)	29.0	34.0	3.99	4.61
PSCC3 (15)	28.0	34.0	3.86	4.61

F_r: measured from the four points loading test on beam specimens.

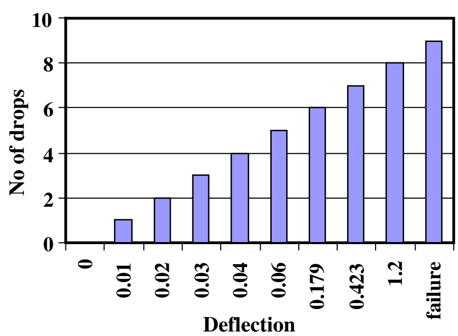

Fig. 21 Relationship between deflection and no of drops of SCC without any Fiber.

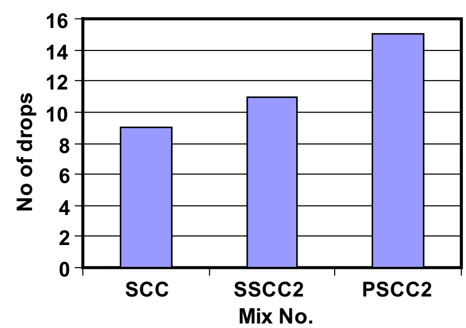

Fig. 24 Relationship between mix no. and no. of drops.

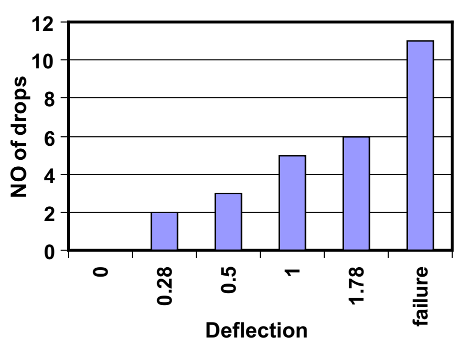

Fig. 22 Relationship between deflection and no of drops of SCC with 0.75% steel fiber.

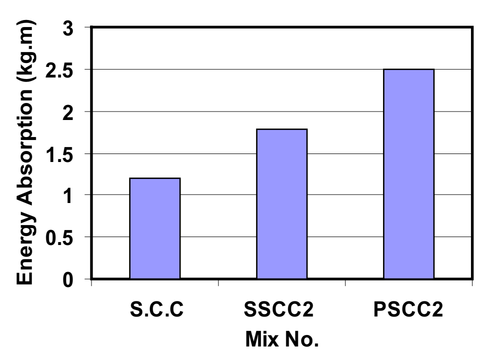

Fig. 25 Relationship between mix no. and energy absorptions.

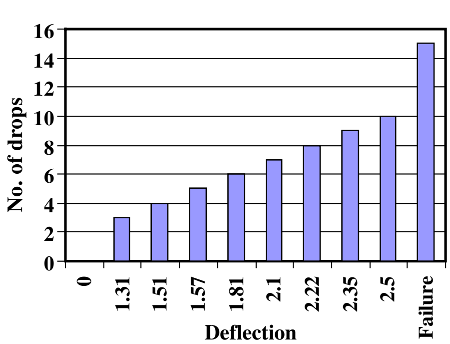

Fig. 23 Relationship between deflection and no. of drops of SCC with 1% polypropylene fiber.

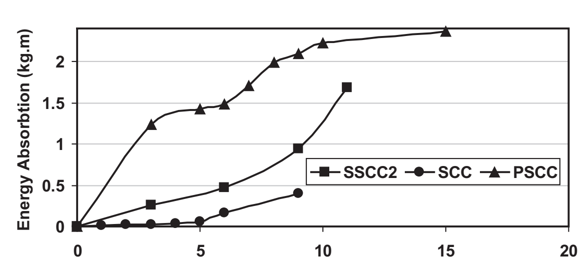

Fig. 26 Relationship between numbers of drops and energy of impact load for different mixes.

masses, velocities, contact zone stiffness, frequency of loading, precision of impact, and the area of local energy absorbed [28–30]. In this study; a drop-weight was used to apply the impact loading to the SCC and fiber SCC beams from a certain drop height. The comparative study of impact energy absorption capacities for each type of concrete was performed. The damage and failure forms were identified.

Impact strength of self-compacted concrete and fiber self-compacted concrete

The number of blows that causes complete failure was 9 blows at 28-day for the control SCC mix. While it ranged between 11 and 15 blows at 28 day for steel fiber and polypropylene fiber SCC mixes. Figs. 21–23 show the numbers of drops and the deflection at different stages of loading for the mixes under investigation. A comparison between the number of drops for SCC and fiber SCC was illustrated in Figs. 24 and 25. The percentage of increase in impact strength was 22.2% and 66.7% for steel fiber and polypropylene fiber SCC, respectively compared with SCC mix. Fig. 26 shows the energy absorption for SCC and fiber SCC.

Conclusions

Based on the test results the following conclusions could be drawn:

(1) The addition of either steel or polypropylene was noticed to enhance the fresh properties of self-compacted concrete by reducing the bleeding.
(2) The optimum content for polypropylene fiber was 1% by cement weight while, the optimum content for steel fiber was 0.75% by cement weight.
(3) Using the polypropylene fibers increased the 28 days compressive strength by 13% independent of the fiber content compared to the control self-compacted concrete mix without fiber addition.
(4) Using the steel fibers increased the 28 day compressive strength by 37% independent of the fiber content compared to the control self-compacted concrete mix without fiber addition.
(5) The impact resistance in terms of the number of drops needed to cause the fracture of test specimens was increased by 22% and 67% when polypropylene and steel fibers were used, respectively.
(6) While the control mix test specimens failed suddenly in flexure and impact, the counterpart specimens contain fibers failed in a ductile manner, and failure was accompanied by several cracks.

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